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# Optical/Millimeter-Wave Double-Resonance Spectroscopy of Rydberg Atoms

**DURIP Grant No. F49620-03-1-0287**

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AFOSR grant F49620-03-1-0287 is a DURIP grant providing laser and millimeter wave instrumentation for the AFOSR sponsored research programs of Robert Jones and Thomas Gallagher at the University of Virginia. The objectives of these two programs entitled "Time Dependent Manipulation of Electronic Wavefunctions" and "Structure and Dynamics of Excited Atoms" are 1. the manipulation of Rydberg atom wavefunctions using sophisticated optical techniques, and 2. using millimeter wave resonance techniques to explore the properties of a frozen Rydberg gas. As described below these research programs can lead to new methods for quantum information processing[1-3] and form a bridge between atomic physic and condensed matter physics.[4]

Highly excited, or Rydberg, atoms have one electron in a state of high principal quantum number n. Since the orbital radius of the Rydberg electron scales as $n^2$ and the binding energy as $1/n^2$, in a Rydberg atom the electron is in a large, weakly bound orbit.[5] Consequently, Rydberg atoms have exaggerated properties relative to ground state atoms. For example, the dipole matrix element for the 30s – 30p transition is 900 $ea_0$ whereas the analogous 2s – 2p matrix element is 4 $ea_0$. The exaggerated properties allow us to study in a controlled way physically interesting problems, such as the exciton like diffusion of population in a frozen Rydberg gas[4-6] and make Rydberg atoms attractive systems for quantum information applications.[1-3]

A single atom is perhaps the smallest device that can be used to store classical or quantum information. For example, in a single atom data register, an electron in its ground state can represent logical 0 while an electron in its first excited state would indicate logical 1. Considerably more data can be stored in a multi-level atom by mapping information into the complex amplitudes of different states in a coherent superposition.[1] Alternatively, instead of using eigenstates for the individual data registers, one could use the spatial distribution of electron probability as a data image.[7] Both of these approaches are considerably more attractive for Rydberg atoms due to the

large spatial extent of the electronic wavefunction and the high density of states of different principal and angular momentum quantum numbers. The key to utilizing Rydberg atoms for either classical or quantum information is the ability to accurately write and read information to and from the atom.

Using the funds provided by this DURIP grant and the associated University matching funds we have been able to purchase a high resolution dye laser and a 20 fs mode locked Ti:Sapphire laser. The high resolution of the former enables us to select single atomic states in an electric field. The Ti:Sapphire laser provides stable spectrally broad pulses which we are using as the starting point for constructing shaped optical pulses. Shaped optical pulses enable us to create coherent superposition states in which the amplitudes and phases of the constituent eigenstates are precisely controlled, allowing us to write information on a single atom and recovery of the information at a later time. The 20 fs laser also allows the generation of sharper half cycle THz pulses which are an important part of our efforts to improve the impulsive momentum retrieval as an information readout technique.

The frozen Rydberg gas, i.e., a sample of Rydberg atoms at a temperature of 1mK and a density of $10^9 cm^{-3}$, exhibits properties similar to ones one might normally expect to see in a solid at a density of $10^{23}$ $cm^{-3}$. The atoms interact with each other through their large electric dipole moments, and this interaction has been proposed as the basis of quantum logic gates. The DURIP funds and associated University matching funds have enabled us to acquire the requisite instrumentation to generate, control, and characterize millimeter waves at frequencies up to 200 GHz with sub kHz linewidths. We have acquired active and passive frequency multipliers, amplifiers, precision attenuators, fast switches, and waveguide hardware. We have used this equipment both to manipulate the populations in the frozen Rydberg gas and as a sensitive spectral

probe of the interactions among the atoms. We have recently verified experimentally that the earlier proposed explanation[5,6] for the anomalous breadth of dipole-dipole energy transfer resonances is correct. Experiments currently underway using the millimeter waves as a spectral probe indicate that the random spacing of the atoms in the Rydberg gas leads to very inhomogeneous samples of atoms, which range from those which are strongly interacting to non interacting.

In sum, the instrumentation provided by the DURIP grant has provided essential new tools for these two AFOSR sponsored research programs.

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